Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24**, 585–603 (1999)

GULLY-HEAD MORPHOLOGY AND IMPLICATIONS FOR GULLY DEVELOPMENT ON ABANDONED FIELDS IN A SEMI-ARID ENVIRONMENT, SIERRA DE GATA, SOUTHEAST SPAIN

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Received 3 November 1997; Revised 4 July 1998; Accepted 17 July 1998

ABSTRACT

In this paper we examine whether gully-head morphology can be used as an indicator for gully development and, hence, for sediment production. A survey was conducted at five hillslopes in the Sierra de Gata where different types of channel heads occur close to each other. The survey included measurements of morphologic and pedologic properties, ground surface, channel and catchment characteristics of every gully head present ($n = 59$). On the basis of the observed morphologies, the heads were subdivided into four types: gradual, transitional (a short inclined section), abrupt and rilled-abrupt. The analyses showed that it is possible to explain the differences of gully heads and the role of some environmental factors on the basis of their morphologies, at least for the gradual and the abrupt types. The results suggested that steep headcuts (abrupt) were formed from secondary headcuts in the channel, which migrated upstream. The abrupt headcuts were always formed in more than one soil layer of which one was a resistant (stony) layer. However, shear strength measurements (at saturation) showed that the top layer was not always the most resistant one. Width–depth relationships indicated that gradual type headcuts were controlled by fluvial processes and abrupt headcuts by a combination of fluvial and mass-wasting processes. Gradual types occurred more downslope than the abrupt types suggesting that the incisions started by fluvial processes and migrated upwards when knickpoints developed in the channel. The rilled-abrupt types are still actively retreating. Thus, the abrupt types correspond to slower retreat rates. Abrupt gully heads may deteriorate into transitional types when plunge-pool erosion becomes less effective. The conceptual model is supported by data from ephemeral gullies in two other study areas (Sierra de la Torrecilla, Spain, and Alentejo, Portugal). Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: gully heads; gully development; gully head morphology; Sierra de Gata; land abandonment

INTRODUCTION

The area of marginal lands that are no longer cultivated in southeast Spain is increasing. These abandoned lands, which are mainly used for grazing, are subject to severe soil erosion, especially gully erosion. Gullies expand upslope by erosion of the gully head. Thus, eroding gully heads form important links between hillslopes and channels and function as zones where sediment is generated, transferred or stored. For example, Oostwoud Wijdenes and Bryan (1994) estimated that after nine storm events about 50 per cent of the sediment output from a small catchment in Kenya was produced by gully-head erosion. Bradford *et al.* (1978) showed that headcuts in the loess region of Iowa temporarily stored sediment after collapse of the headcut. Several storms were needed to evacuate this stored material before headcut erosion occurred again. Leopold *et al.* (1966) reported filling-in of gullies from surveys in the western United States. The authors found that the contributing slopes produced more sediment than the headcut and gully walls. Hence,

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Contract/grant sponsor: European Commission Environment and Climate Research Programme; contract/grant number: ENV4-CT95-0118

CCC 0197-9337/99/070585–19 $17.50

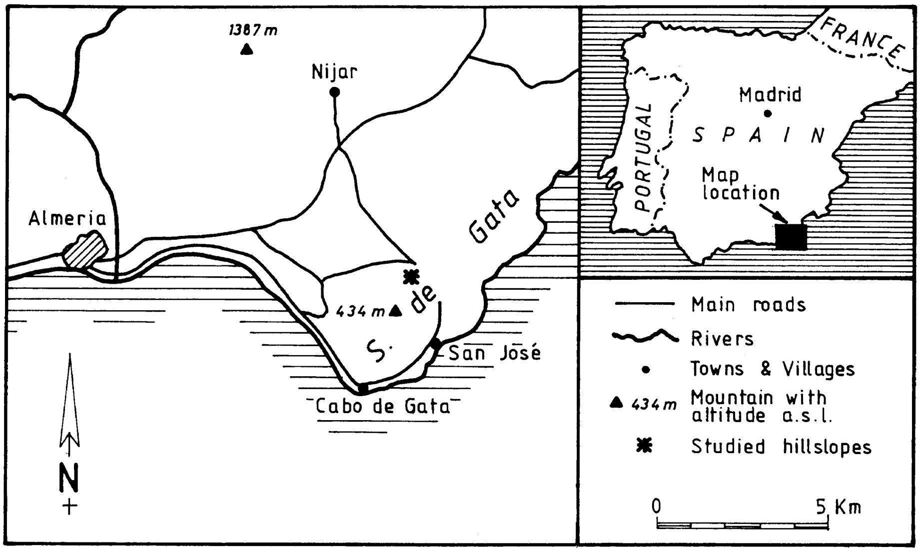

Figure 1. Location of research area

depending on the prevailing sediment balance, channel heads shift up or down the slope or remain in place (Dietrich and Dunne, 1993). Since large amounts of sediments can be involved and land may be lost, it is important that the factors controlling channel-head development are understood. However, the effect of changing environmental factors, including land use and climate, on gully-head erosion is not clearly understood.

Because channel heads occur with very different morphologies, ranging from steep arcuate headcuts to microrills that progressively deepen without abrupt changes, shape might be a useful indicator both of the acting processes and of the evolutionary stage of the gully. Whether the shape of headcuts remains more or less stable or changes in time and/or space during the evolution of a gully is not well documented by means of field studies. Ireland *et al.* (1939) have already shown that gully-head morphologies in the Piedmont region of the Carolinas were associated with distinct processes. Plunge-pool erosion and mass failure were dominant in the case of steep headwalls capped by a resistant B-horizon and fluvial erosion was dominant in the case of gradually sloping heads. Stein *et al.* (1993) have defined criteria for the stability of vertical headcuts from theoretical and laboratory flume experiments based on the ratio of excess shear stresses above, at the edge, and below the headcut. These authors suggested that rotating or self-degrading headcuts occur when the erosion upstream exceeds the erosion downstream of the head. In such cases vertical incision above the headwall is faster than horizontal retreat. In the case of stepped or self-propagating headcuts the erosion of the headwall (by plunge-pool erosion) is so rapid that vertical incision will not be allowed to reach the base. A situation whereby the system changes from a rotating to a stepped state or *vice versa*, may be witnessed in the field by the presence of an incised rill upslope of the headcut.

It is clear that steep-sided headwalls cannot develop or be maintained in some types of material. Therefore, while the form of the headcut may resemble a stage in its evolution that indicates a certain activity of erosion, it may also be merely related to material or environmental properties.

An example of an area where different types of channel heads occur close to each other can be found at the footslopes of the Sierra de Gata in southeast Spain (Figure 1). None of the channel heads belongs to a bank gully (Poesen *et al.*, 1996). All of them developed on the hillslope and are discontinuous. Some channels begin as microrills and progressively widen and deepen. Others start as well defined semi-circular cuts, below which a plunge pool has been scoured by incoming overland flow. The latter are sometimes connected upslope with a rill that feeds runoff directly into the plunge pool. Such channel heads can also be found in

many other semi-arid areas (cf. Malde and Scott, 1977; Imeson and Kwaad, 1980; Oostwoud Wijdenes and Bryan, 1991). Vandekerckhove *et al.* (1998) recently mapped ephemeral gullies in cultivated almond groves in the Sierra de la Torrecilla (100 km north of study area) and in wheat fields in the Alentejo (southeast Portugal). These ephemeral gullies developed after intense rains: 49 mm day^{-1} in the Sierra de Torrecilla and 74 mm day^{-1} in the Alentejo. The authors found that all ephemeral gullies start as microrills which enlarge gradually downstream. However, in fallow fields (montado) in the Alentejo some abrupt gully heads were also observed. Field observations of actively eroding gully heads are rare and difficult to obtain in semi-arid areas (Oostwoud Wijdenes and Bryan, 1994). Therefore, the objective of this paper is to determine whether observed differences in gully-head morphologies can be explained in terms of processes and substrate. To examine this, two research questions have been formulated which will be closely followed:

(1) Can the morphology of gully heads in this area be related to environmental factors such as soil, surface or catchment properties?
(2) Can the morphology of gully heads be used as an indicator for a certain stage in the evolution of the gully?

Here we are specifically concerned with channel initiation and development by concentrated overland flow. In the Sierra de Gata area with a long-term average annual rainfall of 122 mm and gently sloping pediments with shallow compact soils, subsurface flow and seepage seem not to be major factors in gully-head erosion. None of the gullies is controlled by a sudden drop in base level (rambla or terrace bank).

Soil, surface and catchment characteristics

The first question refers to surface or subsurface characteristics that allow headcuts to develop. Rock fragments at the surface may slow down runoff, but they may also concentrate it (Abrahams *et al.*, 1990; Bunte and Poesen, 1994). The same is true for vegetation, which can also trap sediment. The development of a vertical headcut by running water is often associated with the presence of a resistant upper layer. This resistance could be due to a dense root-mat or to the structural stability of the top soil. When such a layer is breached the underlying material is rapidly evacuated leaving a capped steep slope behind. By undercutting of the slope the cap breaks off and the headcut extends upslope. However, laboratory experiments by Bryan and Poesen (1989) have shown small headcut development in homogeneous soil material. During these experiments, secondary headcuts (knickpoints) developed in rill channels which are also common in natural streams. Thus, the presence of a resistant top layer seems not always to be a necessity. However, the strength of the material must be sufficient to support near-vertical walls in wet conditions. When channel slope is smaller than valley slope, the headcut becomes progressively higher when it migrates upslope. Hence, its stability is increasingly determined by its mechanical strength. Mass-wasting, frequently preceded by tension-crack development, is often active at very large headcuts associated with deeply incised channels in valley bottoms or alluvial fans. Finally, Seginer (1966) showed that catchment size affects runoff volumes and, hence, retreat rate. Catchment planform influences flow convergence and divergence at gully heads.

GULLY HEAD EVOLUTION

The second question concerns the initiation of gully heads and their evolution in time. This is closely related to overland flow concentration and the generation of critical shear stresses. Flow concentration may first cause the incision of a rill, after which a knickpoint develops within the channel. If gully heads are not connected with an upslope rill it does not mean that there was no rill when they formed. The headcut could have extended beyond the incision of the rill by headward migration. However, in order to move even further upslope, runoff concentration at the headcut must then result from sheetflow convergence, which requires a certain shape of the catchment. Laboratory flume studies by Bryan and Poesen (1989), Bryan (1990), and Bryan and Oostwoud Wijdenes (1992) showed that small headcuts formed where no rills were before. However, some flow concentration could usually be observed. Whether such small headcuts are comparable with large headcuts is uncertain. A continuous development from rill-sized headcuts to gully-sized ones has not yet been documented.

Mass failure as a result of tension-relief cracks usually tends to widen the headcut while scour and plunge-pool erosion are concentrated at the very upstream tip and keep the channel confined. It can thus be argued that for many channels the size of headcuts reflects prevailing discharge fluxes only if mass-wasting is of minor importance. This would suggest that headcuts grow wider if they reach the upper parts of catchments where runoff volumes decrease.

Enlargement of the headcut (and adjustment of the channel gradient) may also occur as a result of secondary knickpoints moving up the channel and merging with the main headcut. This process has been described by several authors both from field evidence (Bradford *et al.*, 1978) and flume experiments (Bryan and Poesen, 1989; Bryan and Slattery, 1991). De Ploey's (1989) mathematical headcut retreat model showed that smaller secondary headcuts always move faster than the major (bigger) headcut and are therefore likely to join. Secondary headcuts may thus have a significant influence on the primary headcut.

Headcut migration may slow down when mass failure dominates, because much of the fluvial energy is needed to evacuate the failed material and plunge-pool erosion is reduced or is ineffective. Such conditions may also occur when the runoff-contributing catchment declines due to upslope expansion of the gully heads. Plunge-pool erosion will then only destabilize the headcut during infrequent major rainstorm events. When the runoff volumes become very small and the gully head has reached its maximal extension, the steep headwall will eventually decline due to collapse and weathering.

STUDY AREA

The research sites included five hillslopes in the central northwest part of the Sierra de Gata (Figure 1). The slopes are part of the Cerro Pistolas, Cerro Estrada, Cerro Cura, Cerro los Martinez and Cerro Toril. The mountain range consists mainly of volcanic rocks with mostly andesitic parent material at the field sites. The concave–convex slope profiles have gradients varying from 3 per cent in the lower parts up to 50–60 per cent in the upper concave parts. Shallow stony soils are present at the steeper parts (Eutric Leptosols; FAO, 1994) and somewhat better developed soil at the footslopes (Calcic Luvisols; FAO, 1994). Soil depth is sometimes restricted by a petrocalcic horizon close to the surface. The climate is semi-arid with an average annual rainfall of 122 mm and an average annual temperature of 18·6 °C (Walter and Lieth, 1960). Until 10 to 20 years ago, some slopes were still used for wheat cultivation but most of the area has been abandoned for more than 40 years. After abandonment a mixed vegetation of Mediterranean herbs developed including *Anthyllis cytisoides, Chamaerops humilis, Euphorbia Spinosa L.* and *Thymelaea hirsuta.* The upper parts of the slopes were never cultivated and are mainly covered by *Stipa tenacissima.* These areas have very rocky surfaces. Rocky upper slopes underlain by mica schists in the nearby MEDALUS experimental catchment Rambla Honda appeared to be important runoff-generating zones (Nicolau *et al.*, 1996). Aerial photographs show that the largest gullies and many smaller ones were already present in 1957. It was expected that after abandonment, existing gullies expanded and new gullies developed. The aerial photographs confirmed this only for the largest gullies (>2 m in width). Many gullies have a width smaller than 2 m near the headcut, which was beyond the resolution of the photos (scale 1:15 000 and 1: 33 000). Recent research has shown that in many cultivated fields in southeast Spain and northeast Portugal ephemeral gullies quickly developed after major rainfall events (Vandekerckhove *et al.*, 1997). Therefore, it is likely that ephemeral gullying was also active on the slopes of the study area when the fields were still cultivated. After abandonment, newly formed gullies were not obliterated by tillage operations and could expand.

METHODOLOGY

In order to have a consistent data set, five nearby slopes were selected that showed gullying. At each slope all incised channels with cross-sections larger than 929 cm^2 (1 square foot) were included in the survey. This cross-section size was chosen to distinguish gullies from rills (Poesen *et al.*, 1996). On the basis of the observed morphologies, the gully heads were subdivided into four types: gradual, transitional, abrupt and rilled-abrupt (Figures 2 and 3). Gradual types start as small rills and gradually deepen and widen into gullies.

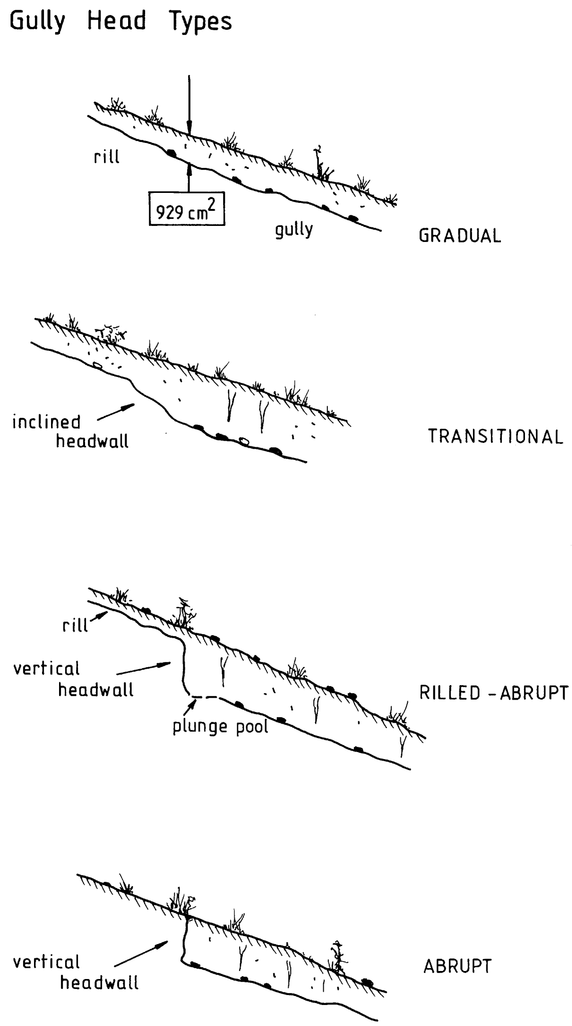

Figure 2. Longitudinal profile of gully-head types

Transitional types showed an inclined channel section. The abrupt types included vertical headwalls. When a rill extended upslope from the headcut, it was classified as rilled-abrupt.

A total of 59 gully heads were surveyed. The parameters included in the survey are shown in Table I. Measuring tapes and clinometers were used to determine length parameters and slope gradient of the soil surface (immediately above and below the gully head) and of the channel bed below the gully head. The drainage area was determined in the field by carefully demarcating the area from which runoff could reach the gully head. Along the axis of this area a base line (measuring tape) was laid out from which at intervals of 5 m orthogonal distances to the drainage divides were measured in opposite directions. This created a pattern of polygons whose summed surface areas provided the total drainage area. Soil shear strength was assessed with a pocket torvane after artificial saturation of the soil layer (Poesen and Govers, 1990). Soil texture was analysed using a Coulter LS-100 (Beuselinck *et al.*, 1998). The rock-fragment cover was estimated by visual observation in the field and photographically according to the point-count method. For that purpose slides were projected on a raster plot with 140 grid points (Poesen *et al.*, 1997)

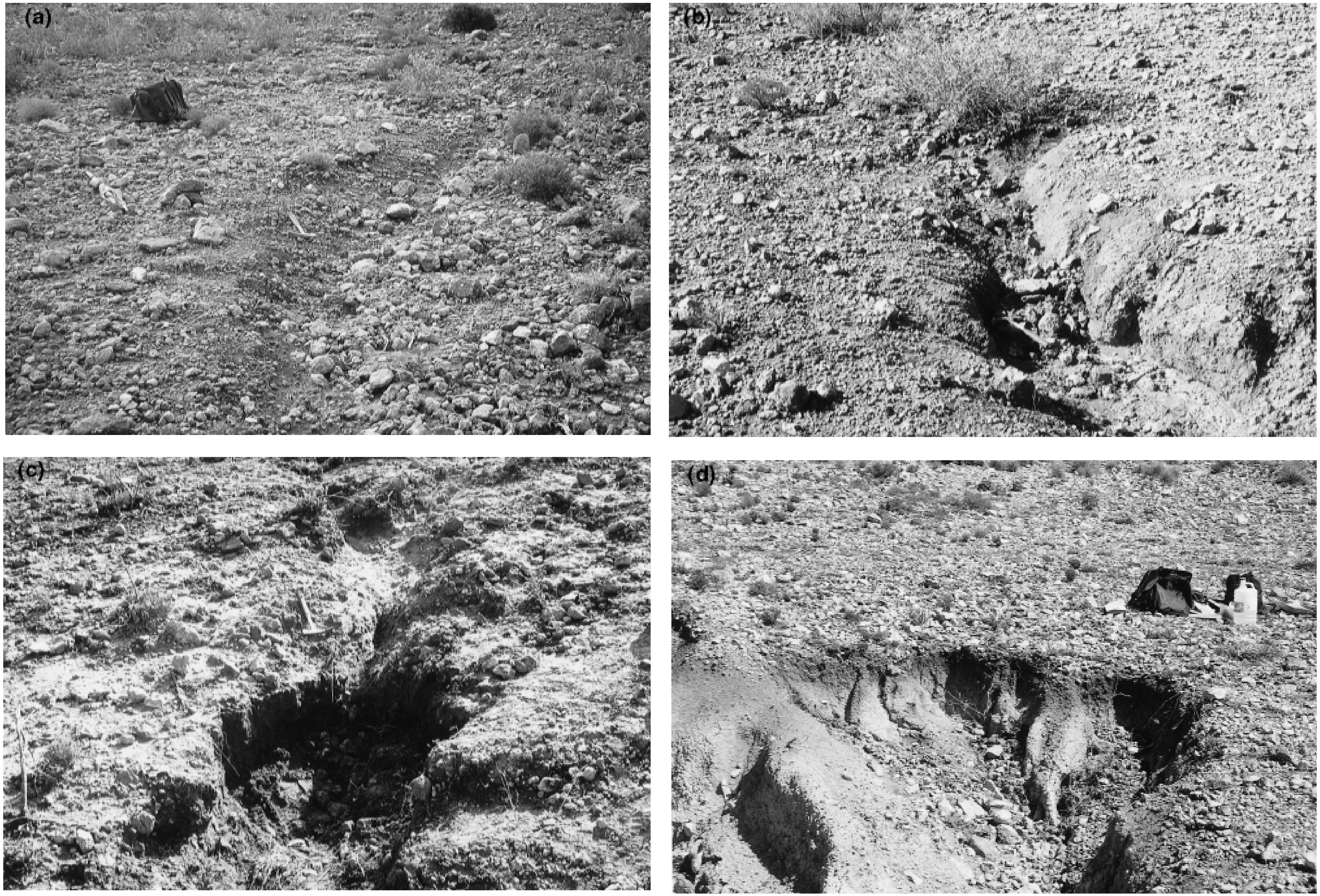

Figure 3. Photo of gully head types: (a) gradual; (b) transitional; (c) rilled-abrupt; (d) abrupt

Table I. Parameters measured in the gully-head survey

Gully-head characteristics	Symbol	units
Length of rill	*L*	(m)
Maximum width of headcut	*W*	(m)
Maximum depth of headcut	*D*	(m)
Slope of headwall		(%)
Presence of plunge-pool	n.a.	yes/no
Catchment area	*A*	(m^2)
Slope gradient above headcut	*S*	(%)
Slope gradient of gully floor	*Sgul*	(%)
Type of land unit: hollow, alluvial fan, etc.	n.a.	n.a.
Soil horizon	n.a.	n.a.
Volumetric rock-fragment content	n.a.	n.a.
Shear strength (wet)	*SH*	(kPa)
Rock-fragment cover	*STs*	(%)
Vegetation: type and cover	n.a.	(%)

Simple statistical methods such as linear correlation and ANOVA (one-way) were used to select those variables that may help to explain evolution of gully heads at a significance level of 5 per cent. When subdividing the sample of 59 gully heads into types ($n = 4$) and sites ($n = 5$), the number of gully heads per group sometimes becomes very low for meaningful statistical analyses. Therefore, the analyses are mostly based on type since morphology is chosen as the differentiating criterion. The sites differ mainly in time since abandonment and not in environmental conditions. The distribution of gully-head types in the Sierra de Gata will be confronted with gully-head types of ephemeral gullies observed in almond groves (Sierra de la Torrecilla, Spain) and of ephemeral gullies found in wheat fields and recently abandoned fallow lands (Alentejo, Portugal).

Aerial photographs of 1957 (1:32 000), 1963 (1:22 000) 1978 (1:18 000) and 1984 (1:20 000) were available for analysis of headcut development and land-use changes.

RESULTS

Gully-head types and spatial distribution

Table II shows the frequencies of each type and their distribution over the different sites in the Sierra de Gata. Also indicated are the ephemeral gully-head types in almond groves in the Sierra de la Torrecilla and the Alentejo. In contrast to the latter study areas, the four types are fairly equally represented in the Sierra de Gata, with 16 gradual, 17 transitional, 13 abrupt and 13 rilled-abrupt. However, the distribution over and within the five sites shows major differences. Most striking is the contrast between the Cerro Pistolas and the Cerro Estrada. Over 47 per cent of the gully heads in the Cerro Pistolas belong to the gradual type. On the slopes of the Cerro Estrada only 20 per cent were classified in this category while the rilled-abrupt occurred most frequently (40 per cent). At the other sites dominant types are less apparent, either because of more equal distribution (Cerro Martinez) or fewer gully heads (Cerro Cura and Toril).

Gully-head types and morphology

Table III includes the summary statistics of the measurements, and a correlation matrix is shown in Table IV that contains the variables for the entire data set. Table IV shows a highly significant correlation between width and depth. The other variables describing the gully-head morphology (width of headcut *W*, depth of headcut *D*, width–depth ratio *WDR*, and length of upslope rill *L*), are not significantly related to each other (the correlation between the width–depth ratio and width and depth are of course spurious). Examination of the distributions shows, however, that the data of the variables do not always fit a normal distribution. There

Table II. Frequency of gully-headcut types at the research sites of the Sierra de Gata, in the Sierra de la Torrecilla and in the Alentejo

Gully-head type	*n*	Cerro Pistolas	Cerro Estrada	Cerro del Cura	Cerro los Martinez	Cerro del Toril	Almond grove S. Torrecilla	Wheat field Alentejo	Recently abandoned Alentejo
Gradual	16	8	3	0	3	2	46	24	14
Transitional	17	3	3	4	4	3	0		
Abrupt	13	3	3	0	4	0	0		1
Rilled-abrupt	13	3	6	2	2	3	0		1
n	59	17	15	6	13	8	46	24	16

n = number of gully heads

Table III. Summary statistics of measured parameters

	L (m)	*W* (m)	*D* (m)	*WDR* (m/m)	*A* (m^2)	*S* (%)	*Sgul* (%)	*SH top* (%)	*SHsub* (%)	*STs* (%)
Combined										
Minimum	0·00	0·30	0·08	0·79	214	6	1	20	15	20
Maximum	55·00	3·10	0·78	16·00	19423	44	57	56	80	70
Mean	7·03	1·02	0·21	5·80	2103	17	15	35	31	53
Median	4·75	0·80	0·15	5·15	1264	14	14	34	32	55
Std. dev.	10·18	0·61	0·15	3·53	3509	8	9	11	13	13
Number	56	59	59	59	49	59	59	37	35	59
Gradual										
Minimum	0·00	0·500	0·08	2·63	430	8	6	20	19	30
Maximum	33·60	1·700	0·19	16·00	5092	31	23	56	80	70
Mean	7·43	0·837	0·14	6·97	1683	16	14	42	33	55
Median	5·80	0·735	0·14	5·76	1469	14	13	44	27	58
Std dev	7·71	0·320	0·03	4·14	1268	7	5	13	18	14
Number	15	16	16	16	13	16	16	11	10	16
Transitional										
Minimum	2·10	0·45	0·11	1·60	265	9	1	20	17	25
Maximum	15·30	1·10	0·45	7·92	16273	44	29	45	38	70
Mean	6·29	0·73	0·17	4·92	2326	19	15	34	29	53
Median	6·40	0·75	0·15	4·67	908	14	15	35	34	55
Std dev.	3·92	0·17	0·08	1·93	3951	11	9	9	8	14
Number	15	17	17	17	16	17	17	11	8	17
Rilled-abrupt										
Minimum	2·20	0·30	0·09	0·79	214	6	2	20	19	35
Maximum	55·00	2·40	0·78	12·44	19423	35	25	40	41	70
Mean	14·44	1·00	0·33	3·92	3262	14	11	30	34	53
Median	8·25	1·10	0·25	3·00	1371	12	9	30	35	55
Std dev.	16·54	0·55	0·19	3·11	6089	8	6	7	7	11
Number	13	13	13	13	9	13	13	8	7	13
Abrupt										
Minimum	0·00	0·44	0·10	3·52	309	6	9	23	15	20
Maximum	0·00	3·10	0·76	15·28	5284	31	57	44	46	70
Mean	0·00	1·65	0·25	7·39	1325	17	21	33	29	53
Median	0·00	1·50	0·18	6·29	1131	16	18	31	25	60
Std. dev.	0·00	0·86	0·18	3·84	1378	6	13	8	13	14
Number	13	13	13	13	11	13	13	7	10	13

L = Length of rill upslope of headcut, *D* = max. depth of headcut, *A* = contributing catchment area, *Sgul* = slope gradient of gully bed, *SHsub* = shear strength of subsoil layer, *W* = max. width of headcut, *WDR* = width–depth ratio, *S* = slope gradient of soil surface upslope of headcut, *SHtop* = shear strength of upper soil layer, *STs* = rock-fragment cover

Table IV. Correcation matrix of gully-head parameters including all types.

	L	*W*	*D*	*WDR*	*A*	*S*	*Sgul*	*SHtop*	*SHsub*	*STs*
L	1 (43)									
W	−0·10 (43)	1 (59)								
D	0·02 (43)	0·43*** (59)	1 (59)							
WDR	−0·08 (43)	n.a	n.a.	1 (59)						
A	0·05 (43)	−0·06 (59)	0·22 (59)	−0·17 (59)	1 (47)					
S	−0·17 (43)	−0·14 (59)	−0·27** (59)	0·03 (59)	−0·27** (47)	1 (59)				
Sgul	−0·22* (43)	0·12 (59)	−0·20 (59)	0·19 (59)	−0·14 (47)	0·66 (59)	1 (59)			
SHtop	−0·17 (43)	−0·14 (59)	−0·15 (59)	0·07 (59)	0·19 (47)	−0·15 (59)	−0·1 (59)	1 (38)		
SHsub	0·07 (43)	−0·16 (59)	−0·06 (59)	−0·20 (59)	0·15 (47)	−0·09 (59)	0·0 (59)	0·4 (38)	1 (32)	
STs	−0·06 (43)	0·02 (59)	−0·11 (59)	0·03 (59)	−0·18 (47)	0·56*** (59)	0·35*** (59)	−0·1 (38)	−0·05 (32)	1 (59)

*** Significant at 1% level
** Significant at 5% level
* Significant at 10% level
n.a. = not applicable
Number of cases is indicated in parentheses
See Table III for explanation of variable names

appears to be a negative skewness in the frequency distributions of the width and the length of the rills. This is due to the presence of more small gully heads than large ones and more short than long rills. A logarithmic transformation of the data improved the normality. However, the transformation did not improve the correlation coefficients.

Examining the data by gully-head type showed that most of these distributions are less skewed than the entire data set. This is partly because the gradual types are usually smaller than the abrupt ones. Table V displays the correlation coefficients for the non-transformed data of gully heads, separated by type. Width and depth are negatively related for the gradual types (Figure 4). Hence, when the cross-section is wider the depth is shallower. For the abrupt types a strong positive correlation was found. This indicates that if the headcut becomes wider it also becomes deeper. This result agrees with reports from the US Soil Conservation Service (1977) and Reid (1982) for abrupt gullies in the USA and Tanzania.

The length of the rill upslope of the headcut (*L*) showed only a weak negative correlation with the width of the transitional headcut types. Width–depth ratio (*WDR*) is weakly negatively correlated with slope for the gradual types (Figure 5). The other gully-head types do not show a statistically significant trend. Statistically significant relationships at the 0·05 and 0·01 level are present in the *WDR* and rock-fragment cover relationships (Figure 6), however, only for the gradual and the transitional types.

Finally, plunge-pools are twice as common at rilled-abrupt as at abrupt or transitional gully heads.

Gully-head types and catchment characteristics

Rock-fragment cover at the surface increased significantly in logarithmic mode with slope gradient which is in accordance with data published by Poesen and Bunte (1996) and Poesen *et al.* (1998). Most surfaces were stony, with Cerro Martinez and Toril significantly stonier than the rest, but rock-fragment cover was not correlated with headcut type. The slope gradients (log-transformed) at gully heads at Cerro Martinez and Toril were also steeper than those of the other areas but gradient did not differ significantly between types.

Table V. Correlation matrices for gradual (A), transitional (B), rilled-abrupt (C) and abrupt (D) gully-head parameters.

	L	*W*	*D*	*WDR*	*A*	*S*	*Sgul*	*SHtop*	*SHsub*	*STs*
(A) Gradual										
L	1 (15)									
W	0·46 (15)	1 (16)								
D	−0·31 (15)	−0·61*** (16)	1 (16)							
WDR	0·47 (15)	n.a.	n.a.	1 (16)						
A	0·10 (15)	0·24 (16)	−0·33 (16)	0·27 (16)	1 (13)					
S	−0·29 (15)	−0·37 (16)	0·32 (16)	−0·46* (16)	−0·58** (13)	1 (16)				
Sgul	−0·35 (15)	−0·39 (16)	0·13 (16)	−0·37 (16)	−0·58** (13)	0·69 (16)	1 (16)			
SHtop	0·20 (15)	0·48 (16)	−0·23 (16)	0·42 (16)	0·36 (13)	−0·32 (16)	−0·19 (16)	1 (11)		
SHsub	−0·17 (15)	−0·22 (16)	−0·09 (16)	−0·21 (16)	0·85 (13)	−0·25 (16)	−0·24 (16)	0·31 (11)	1 (10)	
STs	−0·37 (15)	−0·38 (16)	0·37 (16)	−0·50 (16)	−0·52 (13)	0·69*** (16)	0·34 (16)	−0·19 (11)	0·05 (10)	1 (16)
(B) Transitional										
L	1 (15)									
W	−0·55** (15)	1 (17)								
D	0·0 (15)	−0·13 (17)	1 (17)							
WDR	−0·51** (15)	n.a.	n.a.	1 (17)						
A	0·4 (15)	0·02 (17)	0·35 (17)	−0·27 (17)	1 (16)					
S	−0·2 (15)	−0·03 (17)	−0·38 (17)	0·36 (17)	−0·34 (16)	1 (17)				
Sgul	−0·3 (15)	0·17 (17)	−0·32 (17)	0·36 (17)	−0·19 (16)	0·78*** (17)	1 (17)			
SHtop	0·2 (15)	−0·32 (17)	0·02 (17)	−0·35 (17)	−0·12 (16)	−0·25 (17)	−0·04 (17)	1 (11)		
SHsub	0·3 (15)	−0·62 (17)	0·42 (17)	−0·79** (17)	0·28 (16)	−0·40 (17)	−0·70** (17)	0·38 (11)	1 (8)	
STs	−0·3 (15)	0·47* (17)	−0·67*** (17)	0·72*** (17)	−0·18 (16)	0·63*** (17)	0·69*** (17)	−0·12 (11)	−0·55 (8)	1 (17)
(C) Rilled-abrupt										
L	1 (13)									
W	0·14 (13)	1 (13)								
D	−0·14 (13)	0·27 (13)	1 (13)							
WDR	−0·01 (13)	n.a.	n.a.	1 (13)						
A	−0·18 (13)	0·23 (13)	0·51 (13)	−0·22 (13)	1 (9)					
S	−0·08 (13)	−0·46 (13)	−0·36 (13)	−0·09 (13)	−0·16 (9)	1 (13)				
Sgul	0·13 (13)	−0·27 (13)	−0·30 (13)	−0·04 (13)	0·24 (9)	0·83*** (13)	1 (13)			
SHtop	−0·38 (13)	−0·14 (13)	0·61 (13)	−0·53 (13)	−0·14 (9)	0·39 (13)	0·22 (13)	1 (8)		
SHsub	0·16 (13)	0·10 (13)	0·65 (13)	−0·76** (13)	0·22 (9)	−0·17 (13)	0·10 (13)	−0·04 (8)	1 (7)	
STs	0·17 (13)	−0·51* (13)	−0·11 (13)	−0·27 (13)	−0·03 (9)	0·50* (13)	0·52* (13)	0·50 (8)	−0·08 (7)	1 (13)
(D) Abrupt										
L	-									
W	-	1 (13)								
D	-	0·70*** (13)	1 (13)							
WDR	-	n.a;	n.a.	1 (13)						
A	-	−0·35 (13)	−0·21 (13)	−0·21 (13)	1 (9)					
S	-	0·04 (13)	−0·25 (13)	0·43 (13)	−0·61** (9)	1 (13)				
Sgul	-	−0·01 (13)	−0·23 (13)	0·29 (13)	−0·39 (9)	0·75*** (13)	1 (13)			
SHtop	-	−0·57 (13)	−0·48 (13)	−0·24 (13)	0·37 (9)	−0·13 (13)	−0·21 (13)	1 (8)		
SHsub	-	−0·22 (13)	−0·31 (13)	0·14 (13)	−0·49 (9)	0·51 (13)	0·40 (13)	−0·16 (8)	1 (7)	
STs	-	0·37 (13)	0·04 (13)	0·42 (13)	−0·656** (9)	0·47 (13)	0·11 (13)	−0·18 (8)	−0·07 (7)	1 (13)

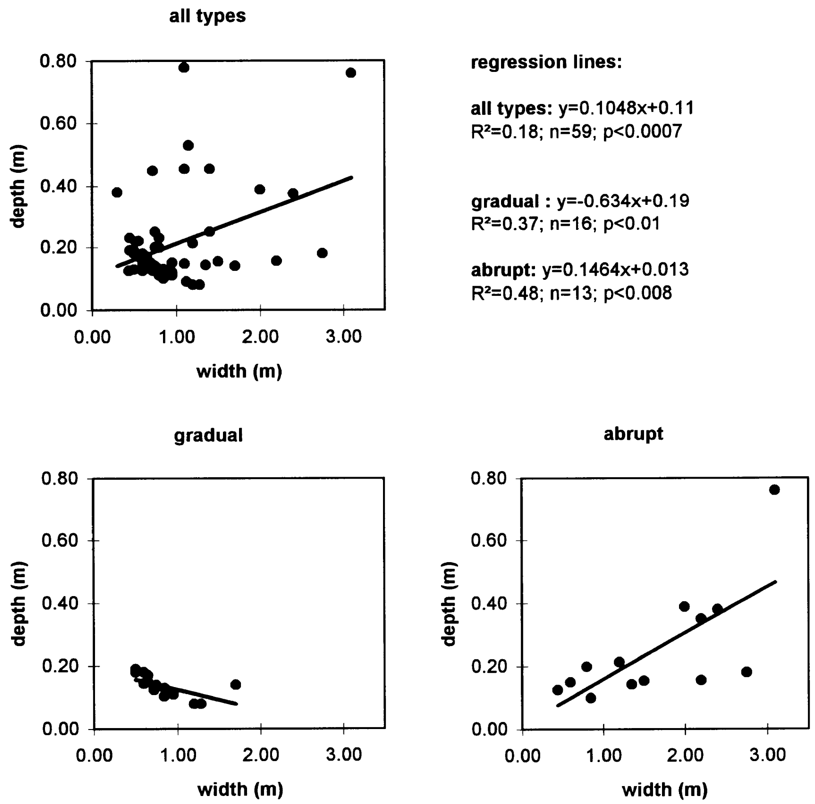

Figure 4. Width–depth relationships for all gully heads and for the gradual and abrupt types

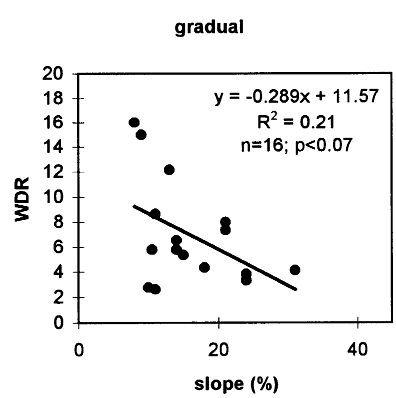

Figure 5. Width–depth ratio (*WDR*) against slope for gradual gully-head type

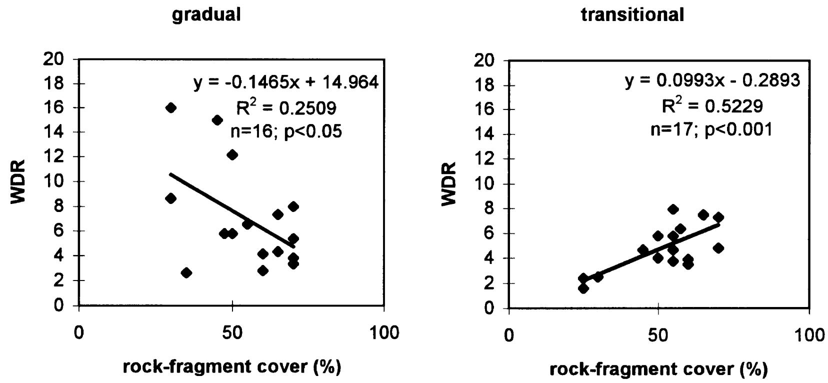

Figure 6. Width–depth ratio (*WDR*) against rock-fragment cover for gradual and transitional gully-head type

On average, the contributing catchments at Cerro Martinez and Toril were the smallest but the data were influenced by outliers in the Cerro Estrada and Pistolas. No significant difference was found between the catchment sizes for the different gully-head types. However, contributing catchment area (A) was strongly negatively correlated with slope gradient at the gully heads (S) after log-transformations. When grouped by type it appeared that no significant relationship was found for the rilled-abrupt type (Figure 7). It should be noted that the trend lines for the gradual, abrupt and transitional types are all very similar.

Cerro Estrada stood out as a site with slightly, but significantly, lower shear strength (log) of the top layer. The gradual type showed the highest shear strength (log) of the top layer but this differed only significantly from the rilled abrupt ones. No sites or headcut types could be separated on the basis of their subsurface shear strength but the difference between shear strength of the top and subsurface layer was largest for the gradual types. The rilled-abrupt types were the only group with an average lower shear strength for their top layer than for the subsurface.

Vegetation cover was always low and the vegetation data showed no correlation with gully-head type.

Aerial photograph interpretation showed that the Cerro Estrada and parts of the Cerro los Martinez were already abandoned and degraded in 1957. Hence, at these sites gullying started more than 40 years ago. The Cerro Pistolas was partly abandoned in 1957, but the research sites were not degraded yet. Therefore, the incisions at the Pistola are younger than those at the Estrada. Headcut extension could only be assessed for four gullies which were wider than 2 m. This sample is too small to be used as an indicator for retreat rates.

Gully-head types and position on the hillslope

The mapped gully heads were separated into three groups, according to their position on the slope (lower, middle and upper). Figure 8A shows, for the whole data set, that the (rilled-) abrupt and transitional headcut types occur mostly at the upper slope sections and the gradual type at the lower and middle section. This pattern is also found at the Cerro Pistola, and the Estrada, except for the transitional heads which occur only at the lower slope at the Pistolas and only at the upper at the Estrada (Figure 8B and C).

DISCUSSION

The examination of the data showed some significant differences between the gully-head types. Therefore, despite somewhat low correlation coefficients, the statistics confirm that the differences observed in the field are real. A major difference between the gradual and the abrupt gully-head types is the relationship between width and depth. However, this is partly due to the definition of a gully used in this study, namely, a cross-section larger than 929 cm^2. The gradual types were all surveyed at approximately this cross-sectional area. The negative correlation between width and depth suggests that the headcut is adjusted to a certain flow

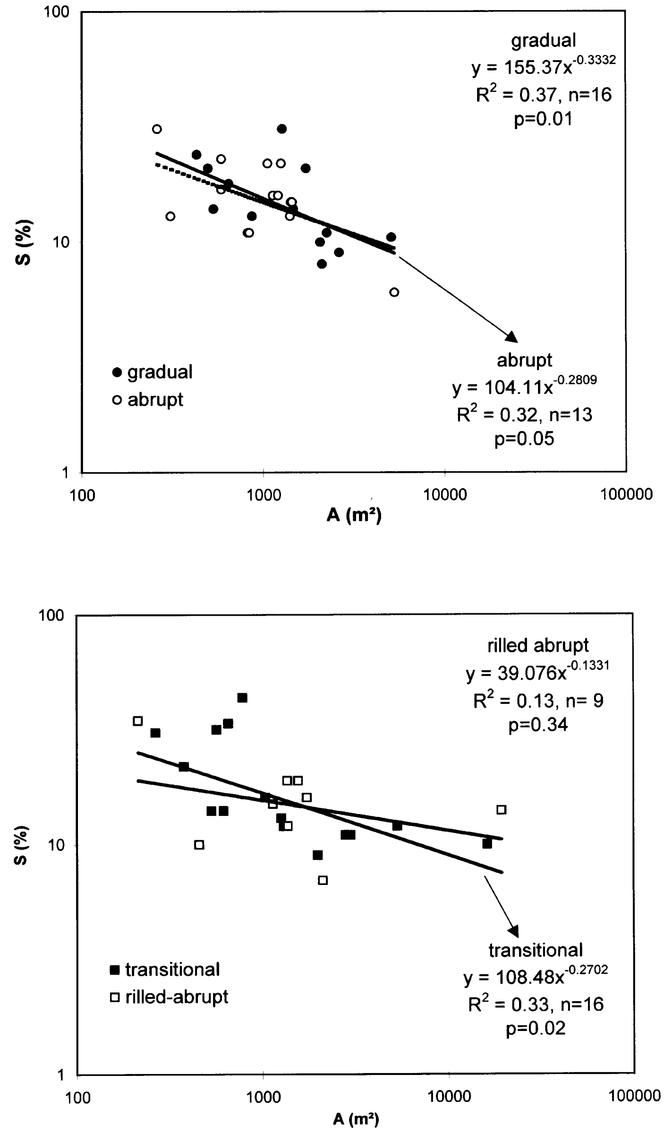

Figure 7. Relationships between soil-surface slope at gully head (S) and drainage area (A) for the gradual and abrupt gully-head types (a) and the transitional and rilled-abrupt types

discharge. Hydraulic erosion of the bed results in deep and narrow headcuts while erosion of the banks results in wide and shallow ones. Thus only fluvial processes are active and no mass-wasting occurs. Abrupt types were more diverse in cross-section. Since there was no relationship between width or depth with contributing catchment size, there is probably also no relationship between width or depth and runoff fluxes. Therefore, the positive width–depth relationship found for the abrupt type indicates that not only fluvial processes are active but also mass movements. Alternatively, variations in material strength dominate-hydraulic geometry; however, this is not indicated by shear strengths. Thus, if the gully head deepens, for example by plunge-pool erosion, the side slopes become unstable and the headcut widens as the walls collapse. The poor correlation between width and depth and catchment area for the transitional and rilled-abrupt types may suggest that sometimes fluvial and sometimes both fluvial and mass-wasting processes operate.

Slope–area relationships have been used to define thresholds for channel-head position (Montgomery and Dietrich, 1994; Prosser and Abernethy, 1996) or for ephemeral gully initiation (Vandaele *et al.*, 1996;

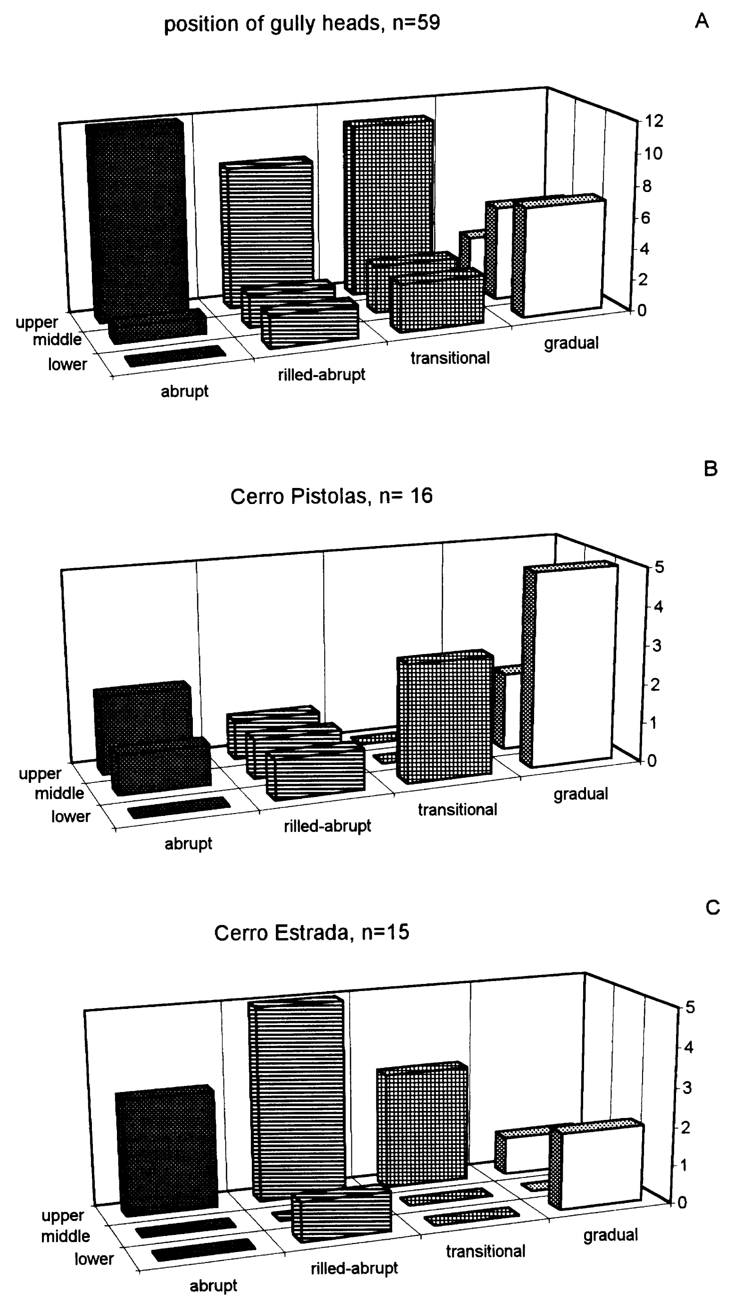

Figure 8. Distribution of gully-head types over slope sections (upper, middle and lower) for entire data set (A), Cerro Pistolas (B) and Cerro Estrada (C)

Vandekerckhove *et al.*, 1998). In this study a significant slope–area relationship was found for the whole data set, but separation into gully-head types showed that the correlation is much weaker for the rilled-abrupt heads (Figure 7). Two possible explanations can be given to account for the substantial scatter in the rilled-abrupt data. First, the rilled-abrupt gully heads receive runoff more frequently than abrupt types because the upslope rill drains the catchment more quickly. Second, in some cases the headcut is still adjusting to the hillslope flow conditions after being initiated as a knickpoint in the channel.

It was stated earlier that there were no significant differences between size in catchment areas of the gully types. Figure 7 does show, however, that the average catchment area of the abrupt types is strongly influenced by one very large catchment (5290 m^2). Because of the presence of many old terraces in the area above the headcut it was difficult to determine the exact size of the runoff-contributing area. Most of the terraces have been included and the original topography was used to demarcate the catchment boundaries. Therefore, its size may have been overestimated. Taking this into account the data do seem to indicate that abrupt gully-head types occur in domains with steeper slopes and smaller runoff-contributing areas. Such zones are typically the upslope areas.

Shear strength at saturation was higher in the top layers of the gradual type than in the rilled-abrupt type. Also, the difference between the shear strength of the top and subsoil was largest for the gradual types. This may seem surprising since resistant layers are often associated with steep headcuts. The result, however, can be explained by the shallow depth of the gradual-type gullies. Many of them had not broken through the upper soil layer, especially at the Cerro Pistolas. Apparently, the shear stresses exerted by the runoff were not powerful enough to break through the top layer. Probably, the cross-section must be larger before that will occur. The high average shear strength of the gradual-type surfaces is also due to the site characteristics of the Cerro Pistolas, where 50 per cent of the gradual gully types occur. Here shear strength is significantly higher than at the Cerro Estrada, where only 12·5 per cent of the gradual gullies occur. Grain-size analyses showed that the topsoil of the Cerro Pistolas contained almost 25 per cent clay, while that of the Estrada contained only 15 per cent. Thus textural differences in the surface layer may well account for the lower shear strength of the Cerro Estrada. The lower average shear strength of the topsoil layer in the rilled-abrupt headcuts coincided with the presence of rills in the softer material and headcuts in the deeper resistant layer. A cap layer was definitely not present. It must, however, be stressed that the hand-held torvane apparatus is difficult to operate in stony soils. The rock-fragment distribution of the soil profile in which the gully heads formed did not show major differences between the gradual, transitional and rilled-abrupt types. However, for the abrupt type just over 75 per cent of the headcuts were developed into very stony material (Figure 9). For the other groups this was always less than half. Thus, although top layers of abrupt headcuts are not always the most resistant, the vertical wall developed into a relatively resistant layer.

The overall trend of gradual gully-head types occurring at the lower slope sections and abrupt types at the upper slope sections is also true for each individual site (Figure 8). However, no major differences in slope gradient were found between types. The pattern of occurrence of the various gully-head types suggests either that gradual types initiate at the lower slope sections and abrupt types more upslope or that the abrupt types started as gradual headcuts and have migrated upslope and are therefore older than the gradual types. Aerial photographs could not be used to detect systematic differences in retreat rates for the different types. This was mainly due to the small size of the gullies, which limited their visibility. However, the photos did reveal changing land-use patterns, in particular the contrast in land degradation between Cerro Pistolas and Estrada. Because Cerro Estrada has been abandoned earlier (no exact dates are available yet), gully expansion also started earlier. At many other cultivated slopes in southeast Spain, ephemeral gullying is widely observed (Vandekerckhove *et al.*, 1998). When these are no longer obliterated by tillage they can develop into permanent gullies after abandonment of the fields. It was observed that ephemeral gully heads are predominantly of the gradual type as they start as small rills. It is therefore assumed that most of the gullies that were examined originated from ephemeral ones and later developed into abrupt headcuts when they migrated upslope.

Summarizing our interpretation, two main groups of headcuts can be identified, the gradual and the abrupt types. After the land was abandoned (or just before the last harvest), gullies developed in the tilled top layer, which were not removed by tillage operations. Most of these incisions started with a rill that widened and

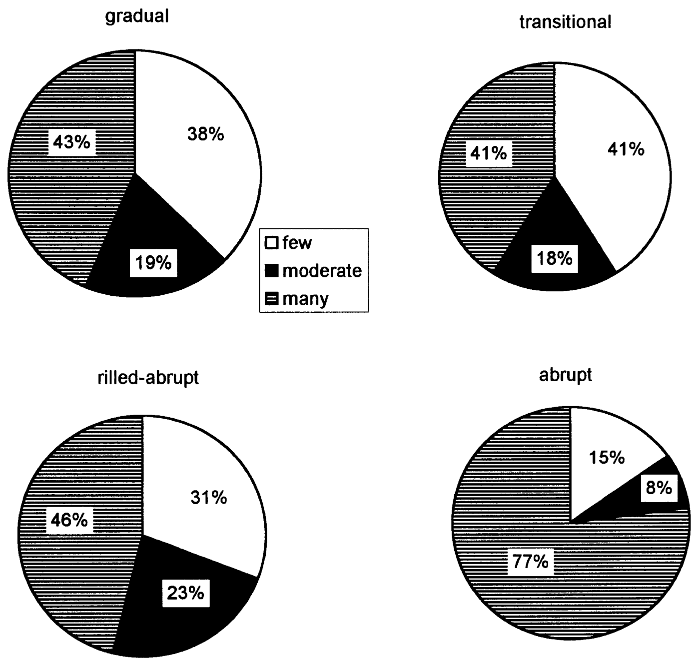

Figure 9. Rock-fragment content (qualitative) of soil profiles at gully heads

deepened progressively in the downstream direction. The critical cross-section which we take as the beginning of a gully effectively moved upstream in time. When the channel at some place cut through a more resistant upper layer, rapid erosion of the underlying layer occurred (cf. Ireland *et al.*, 1939) and a knickpoint developed. This did not necessarily occur at the head but more likely somewhere downstream where shear stresses were higher (many secondary headcuts). A knickpoint can also develop when no resistant upper layer is present (rilled-abrupt). Once a knickpoint was formed it migrated upstream by plunge-pool erosion. No data are available on the morphology of secondary knickpoints; however, it can be argued that due to the increased depth of the channel after the passing of a knickpoint, the side slopes became less stable and mass-wasting processes widened the gully. When the knickpoint reached the head of the rill, the gully head became abrupt. If the cross-section just below the knickpoint exceeded 929 cm^2 but the knickpoint had not reached the beginning of the rill, a rilled-abrupt gully head developed.

Transitional types are less well understood. They can represent an intermediate stage between gradual and abrupt gully heads. However, since these gully-head types are also found on the upper hillslope sections, another possibility is that they are sometimes derived from unstable abrupt headcuts. Instability is caused, for example, when runoff volumes decline after headward extension. Instability is also the result of anisotropic soil and surface conditions. When the headcut retreats into very stony material or surfaces at the upper slopes, an armour of rock fragments develops at the base of the headwall. Considering the low slope gradient of the gully floor, transport of rock fragments can only occur at very high runoff fluxes. Hence, the impact of plunge-pool erosion will be reduced and therefore undercutting of the headwall ceases. The vertical slope will be replaced by an inclined slope. This is supported by the highly significant correlation between width–depth ratio (*WDR*) and rock-fragment cover for transitional types indicating that when the surface becomes more stony the headcut widens (Figure 6). Kirkby and Bull (unpublished data) also found that at sites with many (loose) rock fragments gully heads are characterized by smooth and broad cross-sections.

The concept of rotating headcuts of Stein *et al.* (1993) could apply to the transitional and the rilled-abrupt types. In the case of the transitional types the retreat of the headwall could be so slow that vertical erosion

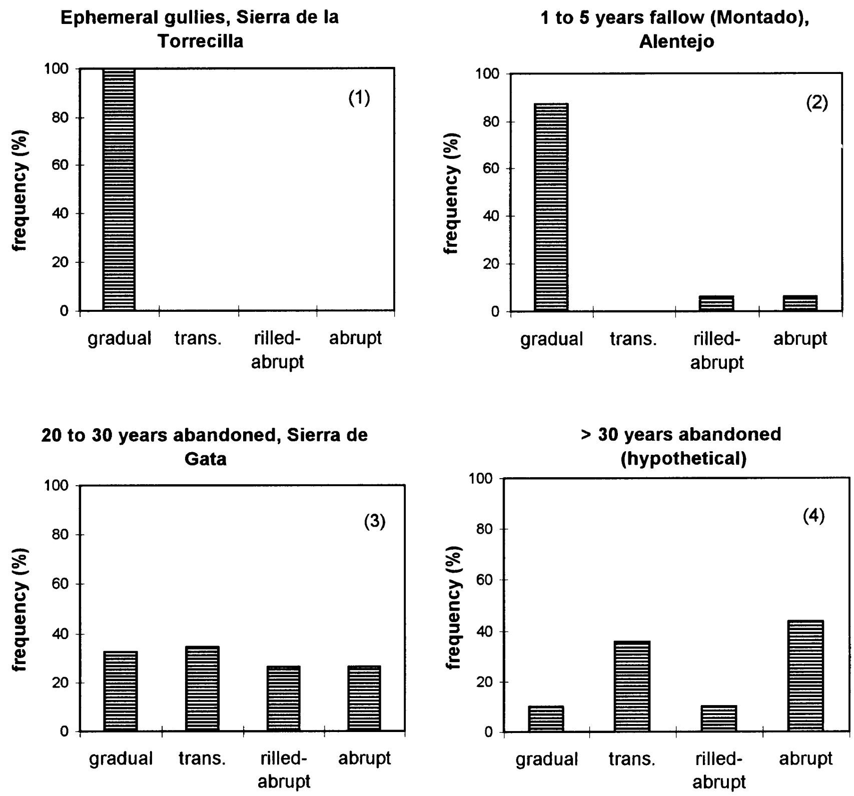

Figure 10. Frequency distributions of gully-head types: (1) intensively cultivated almond groves (Sierra de la Torrecilla, Spain); (2) one to five years fallow land (Montado), Alentejo, Portugal; (3) 20 to 30 years abandoned (Sierra de Gata, Spain); (4) more than 30 years abandoned (hypothetical). Numerical data are given in Table II

dominated the erosion at the head. The rilled-abrupt gully-head type showed vertical incision of the headcut due to lower shear strengths, but only to the depth of a more resistant layer. Plunge-pools are still frequent at the rilled-abrupt types, a condition for stepped retreat.

On the basis of this evolutionary model, the frequency distribution of headcut types in abandoned fields can be used as an indication of the time since abandonment. This is displayed in Figure 10, where the first distribution shows the actual situation for ephemeral gullies in nearby intensively cultivated almond groves (Vandekerckhove *et al.*, unpublished data). The second diagram indicates the distribution after one to five years fallow in the Alentejo (Portugal). The third distribution displays the results from the observations in the abandoned fields in the Sierra de Gata as it follows from this study. The fourth histogram is a hypothetical distribution of a future situation where abrupt and transitional gully-head types dominate. The latter distribution is based on a detailed analysis of the different study sites in the Sierra de Gata. The sites are abandoned for a very long time and almost all gradual and rilled-abrupt gully-head types have evolved into an abrupt type (some of which deteriorated into a transitional type). The heights of the bars in this diagram are only indicative.

CONCLUSIONS AND IMPLICATIONS

In this paper two research questions which concerned the relationship between gully-head morphology and gully evolution were examined. The analyses showed that it is possible to explain the evolution of gully heads

and the role of some controlling factors on the basis of their morphologies, at least for the gradual and the abrupt types. Width–depth relationships seem to indicate that gradual-type headcuts are mainly controlled by fluvial processes. In addition to their location more downslope than the abrupt gully-head types, this suggests that the incisions started by fluvial processes and gully heads migrated upwards when knickpoints developed.

The rilled-abrupt gully-head types are probably still actively retreating until the knickpoint reaches the most upstream point of the incision. Thus, the abrupt type is indicative of slower retreat rates, possibly due to a declining catchment. They may deteriorate into transitional types when plunge-pool erosion becomes less effective. The transitional gully-head types that occur at lower slope sections, for example at Cerro Pistolas, may be indicative of an intermediate stage between a gradual and a (rilled-)abrupt gully head. Thus, the transitional types may represent a terminal stage or a transitional stage towards abrupt types.

Although it cannot be thoroughly substantiated, the presence of secondary knickpoints in the channels and rilled-abrupt gully heads on the slopes may provide a plausible explanation for the development of abrupt gully heads. The abrupt gully heads were always formed in more than one soil layer. However, the top layer was not always the most resistant layer on the basis of shear strength measurements. Yet, the abrupt gully heads were usually developed into a resistant (stony) layer. Abrupt headcuts were mainly found in upslope areas where diffuse overland flow converged at the headcut while inflow into rilled-abrupt headcut was concentrated in rills. The latter type is therefore probably more active than the former due to more effective drainage of the catchment area and the stronger impact of plunge-pool erosion. Their presence is probably determined by the development and migration of secondary knickpoints.

These results apply to the gullies at the footslopes of the Sierra de Gata. A wider application to other abandoned semi-arid lands is only justified if additional data sets are collected. More or less similar types of headcuts can be identified elsewhere. In view of the possible increase of land abandonment in the Mediterranean region there will be a need for appropriate soil-conservation measures. This research could contribute to the development of practical guidelines. For example, the results presented here indicate that the abrupt headcuts, which are often spectacular features in the landscape, are approaching a final stage in their development. However, gradual and rilled-abrupt types are potentially very active and important sediment sources in the near future, and need to be controlled first.

Future research should focus particularly on the role of the secondary knickpoints and sequences of resistant soil layers on gully-head development.

ACKNOWLEDGEMENTS

The research for this study was carried out as part of the MEDALUSIII (Mediterranean Desertification and Land Use Project) collaborative research project. MEDALUSIII was funded by the European Commission Environment and Climate Research Programme (contract: ENV4-CT95-0118, Climatology and Natural Hazards) and this support is gratefully acknowledged. Dr A. Solé (Estacion Experimental de Zonas Aridas, CSIC, Almeria) is thanked for providing information on the study area. Mr Amos permitted access to his land and provided information on the land abandonment which is greatly appreciated.

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